# Torque and electrical power measurements assist in the accuracy of machinery analysis

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Online monitoring of mechanical torque and electrical power is not a new concept. However, the use of such monitoring techniques, as a part of an overall plant predictive maintenance and machinery diagnostic program, is new. New technologies have provided users with reliable, permanently installed transducer systems specifically designed for these purposes. These new transducer systems are now playing an important role in various online, continuous monitoring systems.

Computerization has led to a dramatic increase in the amount of data available to evaluate the mechanical integrity of a given machine train. However, having data available and using the data as a part of a machinery audit are two separate issues. Recent surveys have indicated that in all industrial groups, power generation, petrochemical, pulp and paper, etc., a philosophy of simplicity of analysis has evolved. Such analysis involves trending static, steady state vibration amplitude as opposed to ensuring the accuracy of the analysis by performing a complete machinery audit, which includes, but is not limited to, current steady state data, historical trends, and transient data (both current and historical). However, two additional measurements, dynamic torque and dynamic power, can assist in the accuracy of the analysis.

## Measurement of average and dynamic mechanical torque - TorXimitor®

Shaft power has traditionally been measured with strain gages and a wireless, frequency- modulated (FM) or slip ring data transmission system. The data acquisition package would be installed temporarily while project test data was acquired. Bently Nevada's TorXimitor is a noncontacting, permanently mounted transducer system for continuous, online torque measurements. The transducer system consists of a rotating component attached to the coupling spacer, a stationary component, and an electronic component. The electronic component serves two vital functions. First, it demodulates the signal received from the stationary component and generates an output voltage which is proportional to shaft torque. Secondly, it supplies power to the stationary component.

As the driving machine develops torque to rotate the load, strain develops in the coupling which connects the driver and the load. A strain gage bridge, bonded to the coupling with epoxy, measures the strain. The bridge is a Wheatstone bridge of four active strain gages oriented so they measure the torsional shear strain in the coupling but reject strain due to shaft misalignment, axial loading, and bending. Refer to Figure 1.

The coil assembly in the stationary component uses a tuned oscillating circuit to generate radio frequency (RF) energy that it transmits to the rotating component. The rotating component contains similarly tuned circuits that convert the RF energy into electrical energy. The electrical energy excites the strain gage bridge and powers the electronic circuitry which conditions and filters the strain signal. The conditioned, frequency modulated, strain signal is applied to data transmission plates which encircle the machine coupling (Figure 2). The stationary component receives the strain signal with data transmission plates which match the coupling-mounted plates. The elec-

| Element | Lateral Vibration | Torsional Vibration |
|---|---|---|
| Mass/Inertia | $M = kg$ ($lb \cdot sec^2/in$) | $I = Mr^2 = kg \cdot m^2$ ($lb \cdot sec^2 \cdot in$) |
| Spring | $K = N/m$ ($lb/in$) | $K_r = N \cdot m/rad$ ($lb \cdot ft/rad$) |
| Damping | $D = N \cdot s/m$ ($lb \cdot sec/in$) | $D_r = N \cdot m \cdot s/rad$ ($lb \cdot ft \cdot sec/rad$) |
| Force/Torque | $F = N$ ($lb$) | $T = N \cdot m$ ($lb \cdot ft$) |
| Acceleration | $a = mm/s^2$ ($in/sec^2$) | $a/r = rad/s^2$ |
| Velocity | $v = mm/s$ ($in/sec$) | $v/r = rad/s$ |
| Displacement | $d = mm$ ($in$) | $d/r = rad$ |

Table 1

tronics in the stationary component amplifies the strain signal and transmits it to the electronic component. The electronic component filters electrical noise, demodulates the FM signal, and creates a positive output voltage proportional to the machine torque (Figure 3).

The measured torque has two components, average or static torque and dynamic torque. The average torque is defined as the amplitude of the moment (force couple) applied to a rotor in order to sustain acceleration or load requirements. Dynamic torque is defined as the instantaneous amplitude of the moment applied to a rotor. Dynamic torque is comprised of the average torque plus torque resulting from the torsional vibration of the rotor system at the point of measurement, and is usually expressed in units of N•m (lb•ft) peak to peak.

Torsional vibration is defined as continuous angular oscillatory motion. It can originate from many sources within a mechanical power transmission system. Some of the most common sources for torsional vibration are motor pulsations, unbalanced electrical forces and fluctuating load (torque) requirements. Although torsional vibration problems can seem more complex than lateral vibration problems, it is important to recognize that the two types of vibration phenomena are related. Therefore, the same basic formulas are used to solve both types of problems. In applying the mathematics, the difference between the lateral and torsional systems is the $r$ or $r^2$ factors.[1,3] Refer to Table 1.

### Measurement of average and dynamic electrical power - Dynamic Power Module

For many years, electrical current (ampere) and power (watt) measurements have been made to indicate overall motor load and condition. In recent years, the analysis of the dynamic current signal of electric motors has become more prominent in an attempt to detect malfunctions, such as broken rotor bars, shorted turns, etc. Bently Nevada Corporation has recently investigated the information contained in the dynamic power signal. ►

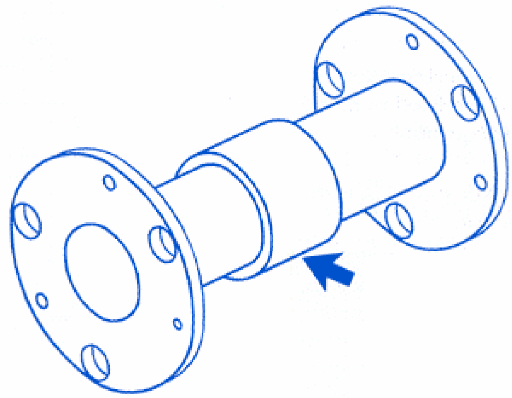

**Figure 1**
**TorXimitor rotating component installed on coupling spool.**

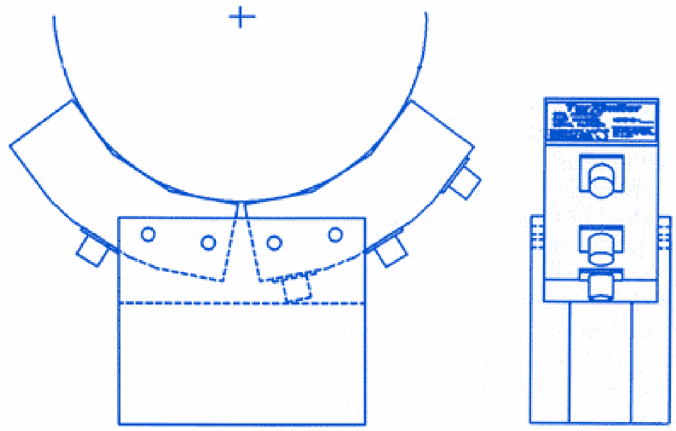

**Figure 2**
**TorXimitor stationary component.**

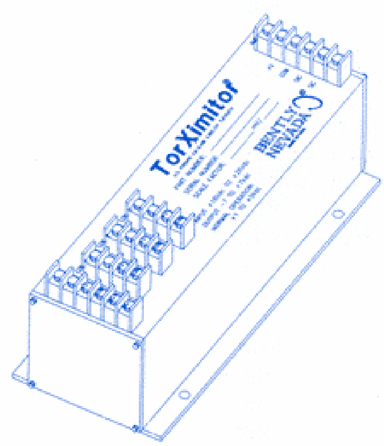


**Figure 3**
**TorXimitor electronic component.**

Motor output power (shaft horsepower) is related to output torque by the equation:

**(1)** $P_O = T_O * S$

where S is machine speed.

Motor input power (electrical watts) is easily measured and is related to motor output power by the equation:

**(2)** $P_O = P_I - P_{LOSS}$

where $P_I$ is input power and $P_{LOSS}$ is the power loss in the motor.

Power losses in an electric motor are due to rotor and stator copper losses, rotor and stator core losses (magnetic), windage and friction. These loss terms are not constant but represent a small percentage of the total power. Additionally, for an induction motor, speed is not constant but varies inversely proportional to motor load. With this in mind, the input power is not directly proportional to, but is related to, output torque.

The dynamic power signal is the instantaneous sum of power dissipated in the three phases of the motor, expressed in units of kW peak to peak. The big advantage to using three phase power instead of single phase power is that the power dissipation for a balanced, three phase load is constant, whereas, for a single phase load, the power dissipation is pulsating. The dynamic power signal for a balanced three phase load is a dc signal.

Bently Nevada Corporation has developed a prototype Dynamic Power Module that connects to current transformers (CTs) and potential transformers (PTs) in a standard two watt meter connection. Figure 4 shows the required connections for the Dynamic Power Module.

The dynamic content of the power signal originates from several sources. These include mechanical load changes; electrical line effects, such as line unbalance, harmonics, and transients; electrical load effects, such as unbalance between phases, and magnetic asymmetries in the motor. Although, related to torque variations, mechanical load changes are of primary interest; the other information contained in the signal is in fact real power delivered to the motor, most of which is delivered to the load.

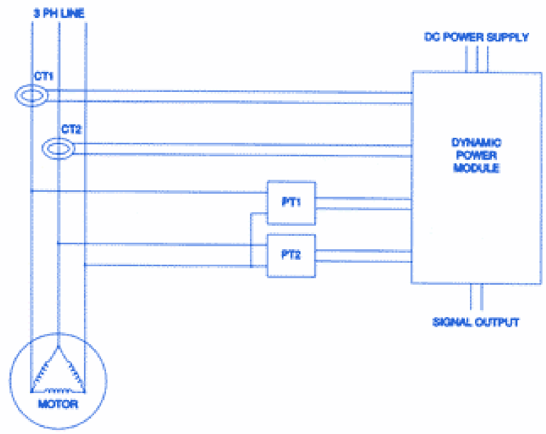


**Figure 4**
**Dynamic Power Module connection.**

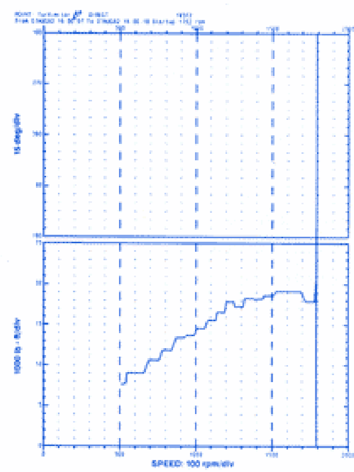

**Figure 5**
**Static torque versus speed during startup.**

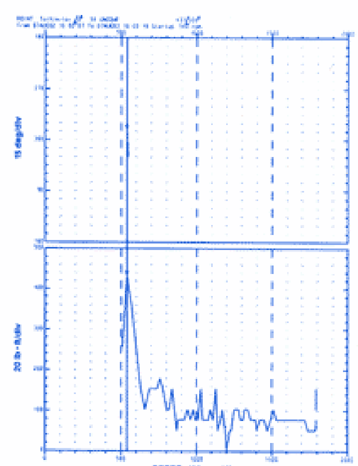

**Figure 6**
**5X dynamic torque, lb•ft peak to peak, transient startup data**


**Figure 7**
**Dynamic torque timebase waveforms, lb•ft peak to peak, acquired during startup.**

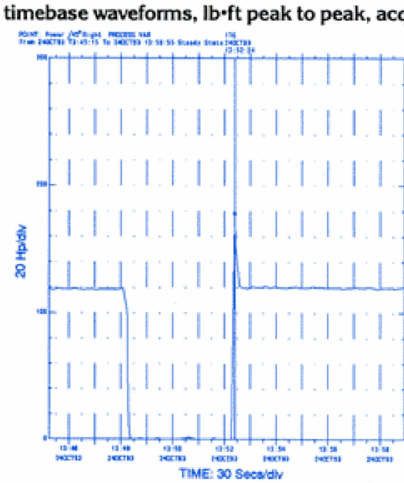


**Figure 8**
**Trend plot of average electrical input power, acquired prior to a shutdown, during startup and at steady state.**

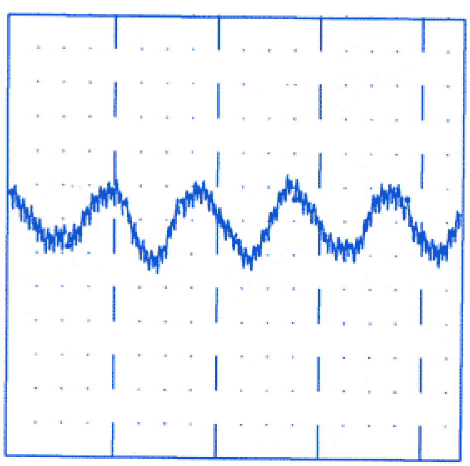

**Figure 9**
**Steady state dynamic power waveform. Scaling is 10 hp/division; overall amplitude is 25.4 hp peak to peak.**

## Example 1: TorXimitor measurements

The data shown in Figures 5 through 7 was obtained from a TorXimitor installation on a large, vertical, single stage pump. The pump is rated at 7,940 hp at 1792 rpm. This equates to a full load torque of 23,270 lb•ft. Figure 5 shows how the average or static shaft torque increases as a function of speed. As described earlier, the measured torque is composed of both average and dynamic components. The average torque imposed on the strain gage produces a dc bias signal proportional to the resulting average strain in the coupling spacer. A maximum static torque of 18,503 lb•ft is reached as the pump obtains rated speed.

These particular pumps have five vanes in the impeller. Therefore, they will generate a 5X vibration component due to the pressure pulsations that occur each time an impeller vane passes the throat of the discharge volute. Computer modeling has predicted that the first torsional resonance for these motor/pump systems should occur at 2971 cpm. Furthermore, the maximum deflection of this torsional resonance occurs at the impeller. Thus, a lateral or torsional forcing function, originating at the impeller, should excite this torsional resonance. The 5X impeller pulsations, therefore, become an excitation force which will excite this torsional mode at an operating speed of 594 rpm[2]. Figure 6 is TorXimitor data which documents the excitation of this torsional resonance by the 5X forcing function at an operating speed of 540 rpm.

Figure 7 shows TorXimitor timebase data at 870 rpm, 1390 rpm, and full speed. The third trace from the top occurs when the pump first reaches 1791 rpm. Note that from one Keyphasor® marker to the next is one revolution of the shaft. However, over that same time period, 1.5 vibration cycles occur. Therefore, the frequency of the vibration is $1.5 \times 1791 = 2686$ cpm. This is the excitation of the first torsional resonance when the pump first reaches 1792 rpm. The torsional response decays within 4 seconds, as is►

indicated by the fourth waveform in Figure 7, which was acquired about four seconds after the third waveform.

### Example 2: Dynamic Power Module measurements

The data shown in Figures 8 through 10 was obtained from a prototype Dynamic Power Module installed on a 200 hp, horizontally-mounted induction motor. The motor operates at 1785 rpm and drives a vertical pump through a right angle gear reducer. Pump speed is 543 rpm.

Figure 8 depicts the trend of the average electrical input power to the motor, $P_1$, as a function of time. The first portion of the plot shows steady state operation with an input power of 119 hp. The motor is shut down and then restarted. During startup, the average electrical input power peaks at 176 hp as the motor reaches 1785 rpm.

Figure 9 is a plot of the unfiltered, steady state, dynamic power waveform at a motor speed of 1785 rpm. Referring to the plot, notice that the overall dynamic power is approximately 25 hp peak to peak.

Figure 10 is a spectrum plot of the same dynamic power waveform. The majority of the dynamic power fluctuation occurs at 60% of pump speed, at 330 cpm, and is equivalent to 14 hp peak to peak. Computer modeling suggests that 330 cpm is the first torsional resonance of the gearbox output shaft and pump rotor. Note that any power fluctuations occurring at 1X are almost indiscernible and that the power oscillations occurring at 1 and 2 times line frequency are quite low. From an electrical perspective, the motor is operating with no significant malfunctions.

### Example 3: Dynamic Power and Torque measurements from the same machine train

Electrical input power and delivered mechanical torque were both measured on a motor driving a screw type air compressor. Motor speed, under full load, is approximately 1781 rpm. The screw compressor is composed of a 4 lobe male screw and a 6 lobe female screw. An internal gearset (83 tooth gear, 40 tooth pinion) increases the speed of the male screw to 3696 rpm, while the female lobe turns at 2464 rpm.

***Frequencies of interest:***

Motor speed: 1781 rpm
Rated efficiency: 97.1%
Male lobe speed: 3696 rpm
Female lobe speed: 2464 rpm

Gearmesh Frequency: $83 \times 1781 =$ 147,823 cpm (2,463.7 Hz)

Lobe mesh frequency: $4 \times 3696 =$ 14,784 cpm (246.4 Hz)

Figure 11 is a trend plot depicting both the average and dynamic input power and average and dynamic torque versus time as the compressor cycles

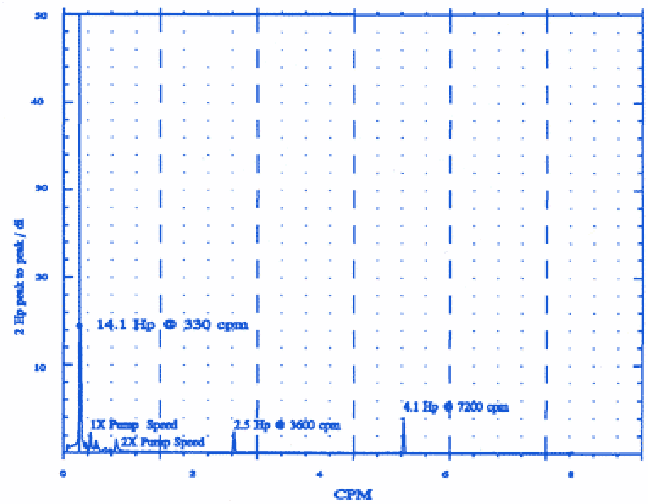


Figure 10
**Dynamic power spectrum. Scaling is 2 hp/division, amplitude at cursor is 14.1 hp peak to peak.**

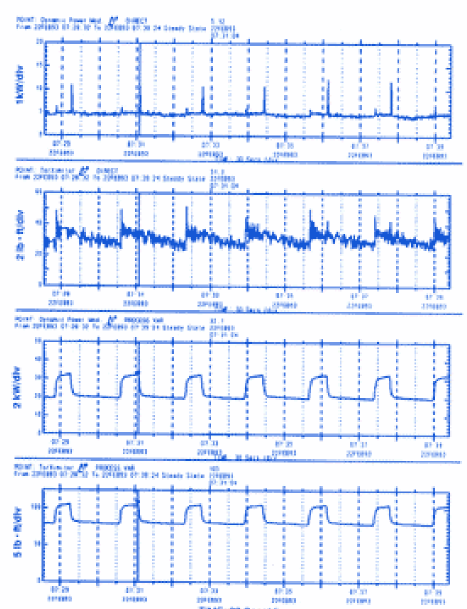


Figure 11
**Top to bottom: Dynamic power, dynamic torque, average power, average torque.**

between full load and no load.

At full load, the motor speed is 1781 rpm, and the average torque, delivered by the motor, is 105 lb•ft.

By definition:

Power (Watts) = $2\pi fT$

where f is frequency in Hz (cycles per second) and T is torque in N•m

Using the conversion factors:

1 minute = 60 seconds

1 lb•ft = 0.737 N•m

1 hp = 745.7 Watts

1 kW = 1000 Watts

We have:

$$\textbf{(3)}\ \text{Hp} = \frac{(\text{Torque, lb•ft})(\text{speed, rpm})}{5252}$$

and:

$$\textbf{(4)}\ \text{Hp} = \frac{(\text{Torque, lb•ft})(\text{speed, rpm})}{7043}$$

Therefore, at full load, the average power delivered by the motor is:

$$\textbf{(5)}\ \text{Power} = \frac{(105\ \text{lb•ft})(1781\ \text{rpm})}{7043} = 26.55\text{kW}$$

Since the average electrical input power was measured as 32.3 kW, the full load efficiency of the motor is calculated to be 82.2%. At no load, the measured average electrical input power was 19.3 kW, while the average torque delivered by the motor was measured at 73.9 lb•ft. The average power delivered by the motor at no load is 18.69 kW, with a calculated efficiency of 97.59%.

The full load dynamic power and dynamic torque timebase waveform and spectrum data plots are depicted in Figures 12 and 13. From the timebase waveform data presented in Figure 12, one observes the absence of any significant dynamic data above 10X motor speed. The spectral data depicted in Figure 13 is presented from 0 to 300 kcpm and also documents the absence of any significant spectral components above 20 kcpm. All dynamic data measurements are peak to peak.

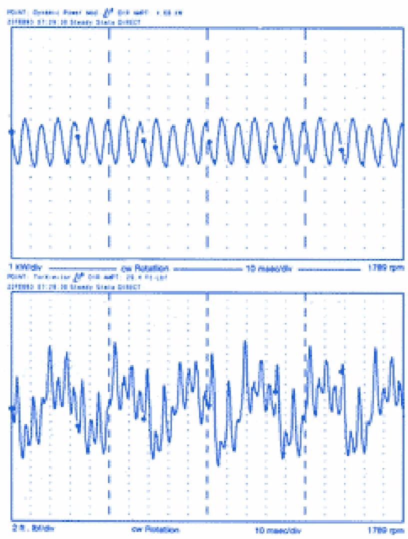


**Figure 12**
**Dynamic power and dynamic torque timebase waveforms.**

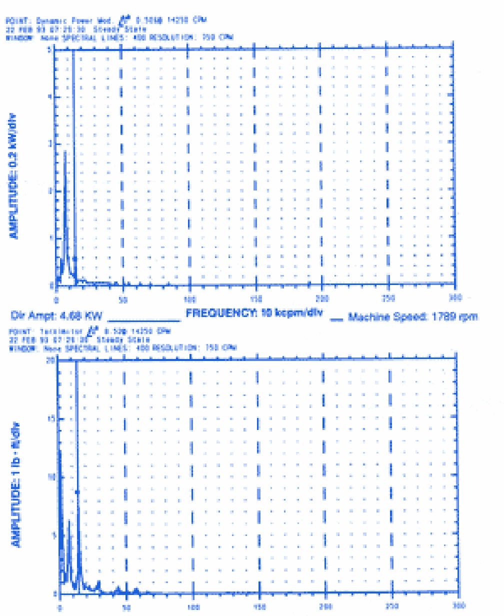


**Figure 13**
**Dynamic power and dynamic torque spectra data.**

## Conclusions

Dynamic power and dynamic torque measurements can be used to augment standard machinery analysis. The information contained in the power and torque data can be very insightful in evaluating the overall mechanical condition of the machine train being audited.

## References


1. John R. Mancuso. *Couplings and Joints - Design, Selection, and Application,* New York, New York: Marcel Dekker, Inc., 1986, pg 370.
2. E. J. Gunter, J. T. O'Brien, "Dynamic Simulation and Model Verification of a Main Coolant Pump to Determine Static and Dynamic Loads," presented at the Fifth International Workshop on Main Coolant Pumps, Orlando, FL (April 1992).
3. Donald E. Bently, Agnes Muszynska, Paul Goldman, "Torsional/Lateral Vibration Cross- Coupled Response Due to Shaft Anisotropy: A New Tool in Shaft Crack Detection," Bently Rotor Dynamics Research Corporation, Minden, NV, BRDRC Report No. 5, 1991.